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Sea-quark flavor asymmetry in the nucleon from a relativistic analysis of the Drell-Yan scattering off nuclei

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The study presented in this paper shows that accounting for the relativistic structure of the deuteron allows to explain the ratio of the Drell-Yan pair production cross-section at the low Bjorken x off the deuteron and the proton. Thus, the sea quark distributions in the nucleon should be studied with accounting for the effects of the relativistic structure of the deuteron. The suggested approach reduces theoretical uncertainty in extracting the ratio $\bar{u}/\bar{d}$ from the data and it is important for the clarification of the nature of the sea quark asymmetry in the nucleon.

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1. Introduction

The Drell-Yan pair production remains up to now the theoretically cleanest way to access sea-quark distributions in hadrons. Necessary stage of such analysis is the measurement both with protons and neutrons, in which sea-quarks with different flavors are probed. As the construction of a target containing free neutrons is not feasible, nuclear targets have to be employed. In the experiment that used the simplest nuclear target — the deuteron, the flavor asymmetry of the sea-quark distributions in the nucleon has been observed [1].

At the same time, analysis of the deep inelastic scattering off different nuclei shows that nucleon valence quark structure changes beyond mass-shell [2]. Recent studies within the Bethe-Salpeter formalism point to the relativistic nature of this phenomenon. Relativistic effects should be manifested as modification of the sea quark distribution in the bound nucleon and, therefore, will change the contribution of the sea quark component in the nucleon structure extracted from the deuteron data. This, in turn, affects estimations of the anti-quark component made by analyzing the deuteron and proton data.

To clarify the role of the relativistic effects in the Drell-Yan (DY) pair produc-

tion, we study this process within the Bethe-Salpeter approach.

2. Drell-Yan Crossection

Since the amplitude for the Drell-Yan scattering is defined by the imaginary part of the amplitude for the forward scattering $\langle A|T(J_\mu J_\nu)|A\rangle$ in the cross-channel, we can obtain it within the Bethe-Salpeter formalism developed for DIS [3]. Within this approach the matrix element is defined by the nucleon space-time distribution and vacuum average of the T-product of the nucleon fields and nucleon electromagnetic current (see Ref. [3]). Following this method we get the following expression of the cross-section for the Drell-Yan scattering off deuteron:

$$\sigma^{\mathrm{pD}}(P,q) = \int \frac{d^4p}{(2\pi)^4} \frac{\sigma^{\mathrm{pN}}(p,q)\, f^{\mathrm{N}/D}(P,p)}{(p^2-m^2)^2\,((P-p)^2-m^2)}. \tag{1}$$

This expression gives the cross-section of the DY pair production off the deuteron in terms of the off-mass-shell DY nucleon cross-section σ^{pN} and the nucleon distribution function $f^{\mathrm{N/D}}(P,p)$. This distribution function is defined by the Bethe-Salpeter amplitudes, and together with the denominator it composes the four-dimensional momentum distribution of the struck nucleon inside the deuteron carrying the total momentum $P = (M_{\mathrm{D}}, \mathbf{P})$. In that way Eq. (1) expresses the nucleon blurring that results from the four-dimensional distribution of the nucleon inside the nucleus. By analogy with the non-relativistic 3D momentum distribution we call it four-dimensional Fermi motion.

Due to the four-dimensional integration in Eq. (1) actual calculations require information about nucleon cross-section σ^{pN} in the kinematical region of the off-mass-shell values of the nucleon energy p_0 ($p_0^2 \neq \mathbf{p}^2 + m^2$). The off-mass-shell behavior of σ^{pN} is unobservable, since then explicit microscopic calculations of the cross-section have no experimental reference and strongly model dependent. Thus, Eq. (1) has to be rewritten in terms of measurable quantities such as the cross-section for DY scattering off the physical nucleon. The simplest solution of this problem is provided by the integration in Eq. (1) with respect to p_0. Analytical properties of the integrand in Eq. (1) give a way to do it explicitly. Within the assumption that $\sigma^{\mathrm{pN}}(p,q)$ and $f^N(P,p)$ are regular with respect to p_0 the integrand contains a second order pole corresponding to the struck nucleon and a first order pole corresponding to the spectator. These poles lie in the different half-planes of the complex plane p_0. So, we can choose one of the singularities to perform the integration. To express the nuclear hadron tensor in terms of the nucleon structure functions it is necessary to choose the second order pole ($p_0 - E_{\mathrm{N}}$) that corresponds to the struck nucleon. The result of the contour integration in vicinity of the second order pole in Eq.(1) is defined by the derivative of the pole residue with respect to p_0 at the point $p_0 = E_{\mathrm{N}}$.

Doing the integration and using the relation in the Bjorken limit $\sigma(P_{\mathrm{p}}, P_{\mathrm{D}}, q) = \sigma(x_1, x_2)$ we get the following expression for the cross section of the DY pair production off the deuteron:

$$\sigma^{\mathrm{pD}}(x_1, x_2^{\mathrm{D}}) = \int \frac{d^3p}{(2\pi)^3} \left[\sigma^{\mathrm{N}}(x_1, x_2^{\mathrm{N}}) - \frac{\Delta_{\mathrm{D}}^{\mathrm{N}}}{E_{\mathrm{N}}} x_2^{\mathrm{N}} \frac{d\sigma^{\mathrm{pN}}(x_1, x_2^{\mathrm{N}})}{dx_2^{\mathrm{N}}} \right] \frac{f^{N/D}(M_D, \mathbf{p})}{8 M_D E_{\mathrm{N}}^2 {\Delta_{\mathrm{D}}^{\mathrm{N}}}^2}, \quad (2)$$

where $x_2^{\mathrm{N}} = x_2^{\mathrm{D}} m/(E_{\mathrm{N}} - p_3)$ is the Bjorken x of the struck nucleon, $E_{\mathrm{N}} = \sqrt{m^2 + \mathbf{p}^2}$ is the nucleon on-shell energy, $\Delta_{\mathrm{D}}^{\mathrm{N}} = M_{\mathrm{D}} - 2E_{\mathrm{N}}$ is equivalent to the total energy shift of the struck nucleon due to the binding and Fermi motion.

The function $f^{\mathrm{N/D}}(M_{\mathrm{D}}, \mathbf{p})$ together with the denominator composes the three dimensional momentum distribution of the struck nucleon inside the deuteron. According to the normalization condition for the Bethe-Salpeter vertex function this distribution satisfies the baryon and momentum sum rules [4] and coincides with the usual nuclear momentum distribution. Thus, the first term in Eq. (2), which results from the derivative of the propagator of the nuclear spectator, expresses contribution of the conventional 3D-Fermi motion.

The second term with $d\sigma^{\mathrm{pN}}(x_{2\mathrm{N}})/dx_{2\mathrm{N}}$ results from the nucleon DIS amplitude derivative:

$$\frac{d\sigma_{\mu\nu}^{\mathrm{pN}}(p, q)}{dp_0} = \frac{dx_2^{\mathrm{N}}}{dp_0} \frac{d\sigma^{\mathrm{pN}}(x_1, x_2^{\mathrm{N}})}{dx_2^{\mathrm{N}}}$$

This term is responsible for the deviation from unity of the ratio of the cross sections. Its contribution is proportional to the coefficient $\Delta_{\mathrm{D}}^{\mathrm{N}}$; which, therefore, characterizes contribution of the four-dimensional Fermi-motion.

It is important to note that the struck nucleon pole gives the factor $1/{\Delta_{\mathrm{D}}^{\mathrm{N}}}^2$, since then the contribution from all other singularities (for example nucleon self-energy cut or anti-nucleon pole) are suppressed at least as $(\Delta_{\mathrm{D}}^{\mathrm{N}}/M_{\mathrm{D}})^2$ [3]. Since the mean value of the energy shift is small $(\Delta_{\mathrm{D}}^{\mathrm{N}}/M_{\prime rmD} \propto O(10^{-2}))$, Eq.(2) provide deuteron Drell-Yan cross-section with accuracy up to terms of order $(\Delta_{\mathrm{D}}^{\mathrm{N}}/M_{\mathrm{D}})^2 \propto O(10^{-4})$.

3. Numerical results

Using the Gluck-Reya-Voght (GRV) parameterization [5] for the σ^{pN} and solution of the Bethe-Salpeter equation with the Graz-II separable kernel [6] as $f^{\mathrm{N/D}}(M_{\mathrm{D}}, \mathbf{p})$ we make numerical calculation fo the ratio $\sigma^{\mathrm{pD}}/\sigma^{\mathrm{pp}}$. It is important to note that the full GRV parameterization is obtained within the approximation $\sigma^{\mathrm{pD}} = (\sigma^{\mathrm{pp}} + \sigma^{\mathrm{pn}})/2$, therefore it already implies isospin asymmetry of the sea-quark distribution in the nucleon in order to describe the DY data. To check influence of the relativistic nuclear effects on the deviations of the ratio $\sigma^{\mathrm{pD}}/\sigma^{\mathrm{pp}}$ from unity we use the GRV parameterization without quark-sea asymmetry $(\bar{u}/\bar{d} = 1)$. The results of the calculation are presented in Fig.1. The dashed curve represents the calculation within the approximation with $\sigma^{\mathrm{pD}} = (\sigma^{\mathrm{pp}} + \sigma^{\mathrm{pn}})/2$, the solid curve represent calculation with the four-dimensional Fermi-motion taken into account.

It is clear from the comparison with the new FNAL data [7], that the relativistic kinematics can reproduce the deviation of the cross-section ration without the flavor asymmetry of the nucleon sea. It is important to note, that the A-dependence of the

deviation is defined by the coefficient $\Delta_A^{\mathrm{N}}/M_A$ in front of the cross-section derivative same as in case of DIS.

Thus, we can conclude that observed flavor asymmetry results from the relativistic kinematics of bound nucleons; the bound nucleon structure change have the same nature in the DIS and DY processes; the effect has the same A-dependence as EMC-effect. A more detailed study of the A-dependence of the effect and high-x data can shed more light on the nature of the sea-quark flavour asymmetry in the nucleon.

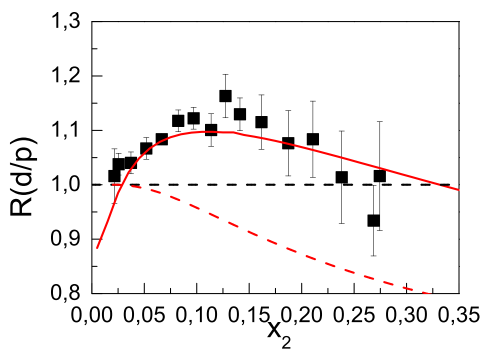

Fig. 1. Calculations of the DY cross-section ratio for the deuteron and proton compared with FNAL E866 (2001) data. The dashed curve is the calculation within the approximation $\sigma^{\mathrm{pD}} = (\sigma^{\mathrm{pp}} + \sigma^{\mathrm{pn}})/2$, the solid curve is the calculation with the four-dimensional Fermi-motion taken into account. Both of the calculation use the GRV parameterization with sea-quark flavour symmetry preserved ($\bar{u}/\bar{d} = 1$).

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References

1. E.A.Hawker et al., FNAL E866/NuSea Collaboration, Phys. Rev. Lett. 80, 3715 (1998)
2. J.J. Aubert et al., Phys. Lett. B123, 275 (1983).
3. V.V. Burov, A.V. Molochkov, G.I. Smirnov, Phys. of Part. and Nucl. Vol. 30, No. 6, 579 (1999).
4. A.V. Molochkov, Nucl. Phys. A666, 169 (2000).
5. M. Glueck, E. Reya, A. Vogt, hep-ph/9806404; European Phys. J. C5, 461, (1998).
6. Rupp G., Tjon J.A. Phys. Rev. C, Vol.41, 471 (1990).
7. R.S. Towell et al., Phys. Rev. D64, 052002 (2001).